Fractional order nonlinear variable speed and current regulation of a permanent magnet synchronous generator wind turbine system

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Abstract In this paper we derived the fractional order model of the Permanent Magnet Synchronous Generator (PMSG) from its integer model. The PMSG was employing a shaft sensor for the speed sensing and control. But this sensor would increase the hardware complexity as well as the cost of the system. Hence we have developed a Fractional order Nonlinear adaptive control method for speed and current tracking of the PMSG. The objective of an adaptive controller is to first define a virtual control state and force it to become a stabilizing function in accordance with a corresponding error dynamics. In order to study the Lyapunov exponents of the fractional order controller, we proposed a new method which would remove the complexity of finding the sign of the Lyapunov first derivative. The Fractional order control scheme is implemented in LabVIEW for simulation results. The simulation results indicated that the estimated rotor position and speed correspond to their actual values well.

1. Introduction

The renewable nature and their reduced environmental impact of Wind energy plays an important role in the present and future power generation methods. Control mechanism of the Permanent Magnet Synchronous Generators (PMSGs) coupled with the wind turbines is of high complexity. Several control strategies of these control mechanisms are investigated by Robinson and Veers [1]. Most of the Wind Energy Generators operate at fixed speed except the initializing phase [2]. Fixed Speed of operation guarantees a high coefficient of performance and these speeds are often fixed for Wind turbines. To operate turbines at these speeds one has to control the Nonlinearity of the speed components [3].

Permanent Magnet Synchronous Motors (PMSMs) are the most preferred generation systems for Wind energy conversions. The chaotic behavior in the permanent magnet synchronous generator for wind turbine system is investigated, and the Active Disturbance Rejection Control (ADRC) strategy is proposed to suppress chaotic behavior and make operating stably [4]. The use of a predictive control strategy...
which was investigated with a one point controller of PMSG is studied and this control mechanism used Genetic Algorithms to estimate the optimal parameter values of the wind turbine leads to maximization of the power generation [5]. PMSG system controlled by the online-tuned parameters of the novel modified recurrent wavelet neural network (NN)-controlled system is proposed to control output voltages and powers of controllable rectifier and inverter [6].

The performance of the PMSM is sensitive to system parameter and external load disturbance in the plant. Some investigations, for example, by Li et al. [7] and Jing et al. [8] show that with certain parameter values, the PMSM displays chaotic behavior. It is found that with the help of fractional derivatives, many systems in interdisciplinary fields can be elegantly described [7–9]. Furthermore many integer order chaotic systems of fractional order have been studied widely [10–14]. All the physical phenomena in nature exist in the form of fractional order [15], and integer order (classical) differential equation is just a special case of fractional differential equation. The importance of fractional-order models is that they can yield a more accurate description and give a deeper insight into the physical processes underlying a long range memory behavior.

Chaos modeling has applications in many areas in science and engineering [15–17]. Some of the common applications of chaotic systems in science and engineering are chemical reactors, Brusselators, Dymamos, Tokamak systems, biology models, neurology, ecology models, memristive devices, etc. An analysis of saddle-node and Hopf bifurcation in indirect field-oriented control (IFOC) drives due to errors in the estimation of the rotor time constant providing a guideline for setting the gains of PI controller (IFOC) drives due to errors in the estimation of the rotor states. As the assumption is made that all the parameters of the PMSG are unknown and hence derived parameter update laws. The stability of the proposed fractional order controllers is established through Lyapunov stability criterion.

2. Fractional order PMSG model

The mathematical model of a Wind turbine coupled PMSG is given by [5]

\[
\begin{align*}
\dot{w} &= \frac{P}{J} (\phi_i i_q + (L_d - L_q) i_d i_q) - \frac{f}{J} w - \frac{T_L}{J} \\
i_q &= -\frac{R_s}{L_q} i_q + \frac{L_d}{L_q} p w i_d - \frac{p \phi_f}{L_q} w + u_q \\
i_d &= -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} p w i_q + u_d \\
\end{align*}
\]

where \( u_q \) and \( u_d \) are quadrature and direct axis stator control voltages, \( i_q \) and \( i_d \) are quadrature and direct axis stator control currents, \( L_q \) and \( L_d \) quadrature and direct axis stator control inductances, \( p \) is the number of pole pairs, \( R_s \) is the stator resistance, \( \phi_f \) is the rotor flux linkage with stator, \( T_L \) is the Load torque, \( J \) is the rotor moment of inertia, and \( f \) is the friction coefficient.

The fractional-order differential operator is the generalization of integer-order differential operator. There are three commonly used definitions of the fractional-order differential operator, viz. Grunwald–Letnikov, Riemann–Liouville and Caputo [23–25].

The fractional order model of PMSG is derived from (1) with the Caputo fractional order definition, which is defined as

\[
D^\alpha_t f(t) = \frac{1}{\Gamma(1 - \alpha)} \int_{t_0}^{t} \frac{f(\tau)}{(t - \tau)^\alpha} d\tau
\]

where \( \alpha \) is the order of the system, \( t_0 \) and \( t \) are limits of the fractional order equation, and \( \hat{f}(t) \) is integer order calculus of the function.

For numerical calculations we use Caputo via Riemann–Liouville fractional derivative [26] and the above equation is modified as

\[
(t - t_0)^{\alpha-1} D^\alpha_t f(t) = \lim_{h \to 0} \frac{1}{h^\alpha} \sum_{j=0}^{N(t)} b_j f(t - jh)
\]

Theoretically fractional order differential equations use infinite memory. Hence when we want to numerically calculate or simulate the fractional order equations we have to use finite memory principle, where \( L \) is the memory length and \( h \) is the time sampling.

\[
N(t) = \min \left\{ \left\lfloor \frac{t}{L} \right\rfloor, \left\lfloor \frac{L}{h} \right\rfloor \right\}
\]

\[h_j = \left( 1 + a + \frac{a}{L} \right) b_{j+1}
\]

Applying these fractional order approximations into the integer order model (1) yields the fractional order PMSG described by (5)

\[
\begin{align*}
D^\alpha_t \tau &= \frac{P}{J} (\phi_i i_q + (L_d - L_q) i_d i_q) - \frac{f}{J} w - \frac{T_L}{J} \\
D^\alpha_t e_i &= -\frac{R_s}{L_q} i_q + \frac{L_d}{L_q} p w i_d - \frac{p \phi_f}{L_q} w + u_q \\
D^\alpha_t e_d &= -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} p w i_q + u_d 
\end{align*}
\]

where \( q_1 \), \( q_2 \) and \( q_3 \) are the fractional orders of the respective states.

As the assumption is made that all the parameters of the PMSG model are uncertain, we are defining parameter update laws:

\[
\begin{align*}
\tau &= \hat{\tau} - \tau; \ e_i = D^\alpha_t \hat{\tau}; \ b = \frac{f}{J}; \ e_d = \hat{b} - b; \ D^\alpha_t e_R = D^\alpha_t \hat{b} \\
e_e &= \hat{R}_d - R_d; \ D^\alpha_t e_R = D^\alpha_t \hat{R}_d; \ e_L = \hat{L} - L; \ D^\alpha_t e_L = D^\alpha_t \hat{L} \\
e_j &= \hat{J} - J; \ D^\alpha_t e_j = D^\alpha_t \hat{J}
\end{align*}
\]

3. Dynamics of the fractional order PMSG model

In this section we analyze the fractional order system for various properties of chaotic behavior such as equilibria points, Lyapunov exponents, bifurcation and bicoherence.
3.1. Equilibria points and Lyapunov exponents

The equilibria of the system (5) can be found by solving (7):

\[
\begin{align*}
0 &= x \left( y - x \right) + ze y \\
0 &= -y - xz + bx \\
0 &= -z + xy
\end{align*}
\]

The three equilibria points of the system (5) are

\[E_1 = (0, 0, 0) \text{ and } E_{2,3} = (\gamma - 1, \pm \sqrt{\gamma - 1}, \pm \sqrt{\gamma - 1})\].

And the Jacobian matrix of the system (7) is defined as,

\[
J = \begin{bmatrix}
-a & a + ez & ey \\
-z & b & -1 \\
y & x & -1
\end{bmatrix}
\]

where \(x, y \& z\) denotes the equilibrium points.

The initial conditions are chosen as \(x = 3, y = 3 \& z = 3\) and the parameter values are chosen as \(a = 5.45, b = 20, \varepsilon = 1\). The Lyapunov exponents of the system (5) are \(L_1 = 0.852023, L_2 = -0.009746, L_3 = -8.502219\). The numerical results of the simulation are shown in Fig. 1.

3.1.1. Bifurcation and bicoherence

By fixing \(a = 5.45, a\) is varied and the behavior of the fractional order system (5) is observed in Fig. 2. By fixing \(b = 20\), \(b\) is varied and the system (5) performance is observed in Fig. 3. Generally speaking, when the system’s biggest Lyapunov exponents are large than zero, and the points in the corresponding bifurcation diagram are dense, the chaotic attractor will be found to exit in this system. Therefore, from the Lyapunov exponents and bifurcation diagrams in Figs. 2 and 3 a conclusion can be obtained that chaos exit in the fractional order PMSM system (5) when selecting a certain range of parameters.

The bifurcation plots of the system (5) with the change in the order of the system and the parameters are fixed at \(b = 20, a = 5.46\). Fig. 4 shows the order \(q_1, q_2, q_3\) varied and the attractor bifurcation responses are investigated. As seen from the bifurcation plots, the system chaotic dynamics changes drastically with the fractional order. By comparing the Eigen values and the Lyapunov exponents with the fractional order bifurcation graphs, it can be commented that as the order of the fractional equation lies between 0.6 \(\leq q \leq 0.9\), the systems chaotic behavior is showing larger Lyapunov exponents. Hence the chaos suppression with fractional order controllers is efficient than the integer order control algorithms.

The bicoherence or the normalized bispectrum is a measure of the amount of phase coupling that occurs in a signal or between two signals. Both bicoherence and bispectrum are used to find the influence of a nonlinear system on the joint probability distribution of the system input. Phase coupling is the estimate of the proportion of energy in every possible pair of frequency components \(f_1, f_2, f_3, \ldots, f_n\). Bicoherence analysis is able to detect coherent signals in extremely noisy data, provided that the coherency remains constant for sufficiently long times, since the noise contribution falls off rapidly with increasing \(N\).

The auto bispectrum of a chaotic system is given by Pezeshki [22]. He derived the auto bispectrum with the Fourier coefficients.

\[
B(o_1, o_2) = E[A(o_1)A(o_2)A^*(o_1 + o_2)]
\]

where \(o_0\) is the radian frequency and \(A\) is the Fourier coefficients of the time series. The normalized magnitude spectrum of the bispectrum known as the squared bicoherence is given by

\[
b(o_1, o_2) = \left| B(o_1, o_2) \right|^2 / P(o_1)P(o_2)P(o_1 + o_2)
\]

where \(P(o_1)\) and \(P(o_2)\) are the power spectrums at \(f_1\) and \(f_2\) (see Figs. 5–7).

Figure 1  Dynamics of Lyapunov exponents.
4. Nonlinear adaptive control design

The objective of an adaptive controller is to first define a virtual control state and force it to become a stabilizing function in accordance with a corresponding error dynamics. The error dynamics can be stabilized by properly selecting the control input through the Lyapunov Stability theorem. Firstly the speed tracking error is defined by (11). The fractional orders $q_1$, $q_2$, $q_3$ are taken as $a$.

\[ e = x - x_d \]  

(11)

The fractional derivative of the speed tracking error is given by (11) and (5) as (12),

\[ D_a^e = \dot{\omega} - \dot{x}_d = \frac{p}{J} (i_q l_d) - f \omega - \frac{T_L}{J} - \dot{x}_d \]  

(12)

where $\dot{x}_d$ and $\dot{x}_d$ are the desired quadrature and direct axis stator current values respectively. The error dynamics in (9) has to be stabilized using the proposed controller to make the rotor angular speed $\omega$ track the reference value $\omega_d$. We here use a well-known back stepping procedure to derive the modified fractional order speed tracking error dynamics which is obtained by solving (13) and (5) in (12):

\[ D_a^e = \frac{p}{J} e_q + \frac{p}{J} i_{qd} - b_\omega - \tau - \dot{x}_d \]  

(14)

In order to stabilize the fractional order speed tracking error dynamics (14), we assume the current tracking desired values are assumed as (15),

\[ i_{qd} = \frac{J}{p\phi_f} (b_\omega + \dot{\omega} + \dot{x}_d - k_1 e) \]  

\[ i_{dd} = 0 \]  

(15)

where $k_1$ is the feedback gain. By solving (14) using (15) and (5), we derive the modified speed tracking error dynamics (16),

\[ \frac{p}{J} e_q + \frac{p}{J} i_{qd} - b_\omega - \tau - \dot{x}_d \]
Using \( i_q \) equation from (5) and (6) and \( i_{qd} \) from (15)

\[
D_t^\alpha e_q = \frac{p\phi_q}{J} e_q + \frac{j}{J} (b_0 + \dot{\omega} + \omega_d - k_1 e) \tag{16}
\]

Using \( i_q \) equation from (5) and (6) and \( i_{qd} \) from (15)

\[
D_t^\alpha e_q = l_q - i_{qd} \tag{17}
\]

\[
D_t^\alpha e_q = -\frac{R}{L} i_q + p\omega_d - \frac{p\phi_f}{L} \omega + \frac{u_q}{L} + \frac{D_t^\alpha j}{p\phi_f} (b_0 + \dot{\omega} + D_t^\alpha \omega_d - k_1 e) - \frac{J}{p\phi_f} \left( D_t^\alpha b_0 + b D_t^\alpha \omega + D_t^\alpha \dot{\omega} + D_t^\alpha D_t^\alpha \omega_d - k_1 (D_t^\alpha \omega - D_t^\alpha \omega_d) \right) \tag{18}
\]

Substitute \( \dot{\omega} \) from (1) in (18)

\[
D_t^\alpha e_q = -\frac{R}{L} i_q + p\omega_d - \frac{p\phi_f}{L} \omega + \frac{u_q}{L} - \frac{D_t^\alpha j}{p\phi_f} (b_0 + \dot{\omega} + D_t^\alpha \omega_d - k_1 e) - \frac{J}{p\phi_f} \left( b D_t^\alpha \omega - k_1 D_t^\alpha \omega \right) \tag{19}
\]

A slight modification of (19) yields (20)
\[ D_t^\alpha e_q = - \frac{R_i}{L_e} i_q + \frac{p o i L_d}{L} + \frac{p o e L_i}{L} + u_q \]
\[ - \frac{D_t^\alpha j}{p o \phi_f} (b o + t + D_t^\alpha o_d - k_1 e) \]
\[ - \frac{j}{p o \phi_f} (D_t^\alpha b o + D_t^\alpha \dot{t} + D_t^\alpha D_t^\alpha o_d + k_1 D_t^\alpha o_d) \]
\[ - \frac{j}{p o \phi_f} (b - k_1) (p (\phi_f i_q) - b o - \tau) \]
(20)

Redefining (20) and applying parameter estimation errors from (6), we can arrive at (21),
\[ D_t^\alpha e_q = - \frac{R_i}{L_e} i_q + \frac{e_R}{L} i_q + \frac{p o i L_d}{L} + \frac{p o e L_i}{L} + u_q \]
\[ - \frac{D_t^\alpha j}{p o \phi_f} (b o + t + D_t^\alpha o_d - k_1 e) \]
\[ - \frac{j}{p o \phi_f} (D_t^\alpha b o + D_t^\alpha \dot{t} + D_t^\alpha D_t^\alpha o_d + k_1 D_t^\alpha o_d) \]
\[ - \frac{j}{p o \phi_f} (b - k_1) i_q - \frac{j}{p o \phi_f} (b) \]
\[ - k_1 (b - e_i) o + (b - e_i) \]
(21)

Simplifying (21) and rearranging the inertial error terms,
\[ D_t^\alpha e_q = - \frac{R_i}{L_e} i_q + \frac{e_R}{L} i_q + \frac{p o i L_d}{L} + \frac{p o e L_i}{L} + u_q \]
\[ - \frac{D_t^\alpha j}{p o \phi_f} (b o + t + D_t^\alpha o_d - k_1 e) \]
\[ - \frac{j}{p o \phi_f} (D_t^\alpha b o + D_t^\alpha \dot{t} + D_t^\alpha D_t^\alpha o_d + k_1 D_t^\alpha o_d) \]
\[ - \frac{j}{p o \phi_f} (b - k_1) i_q - \frac{j}{p o \phi_f} (b - k_1) i_q - \frac{j}{p o \phi_f} (b - k_1) (e_o o + e_i) \]
(22)

From (1) and (6) and solving for (13) with assuming \( i_{ad} = 0 \)
\[ D_t^\alpha e_d = D_t^\alpha i_d - D_t^\alpha i_{dad} \]
(23)

Using (1) and simplifying Eq. (19),
\[ D_t^\alpha e_d = - \frac{R_i}{L_e} i_d + \frac{p o i L_d}{L} + v_d \]
\[ - \frac{R_i}{L_e} i_d + \frac{e_R}{L} i_d + \frac{p o i L_d}{L} + \frac{p o e L_i}{L} + u_d \]
\[ = \frac{(R_i - e_R)}{L} i_d + \frac{p o i L_d}{L} i_d + \frac{v_d}{L} \]
\[ \frac{R_i}{L_e} i_d + \frac{e_R}{L} i_d + \frac{p o i L_d}{L} i_q + \frac{p o e L_i}{L} i_q + \frac{v_d}{L} \]
(24)

To stabilize the current tracking error dynamics we can define the controllers as,
\[ v_d = \frac{R_i}{L_e} i_d - \frac{p o i L_d}{L} + \frac{p o e L_i}{L} - k_2 L e_i \]
\[ + \frac{L}{p o \phi_f} \frac{D_t^\alpha j}{p o \phi_f} (b o + t + D_t^\alpha o_d - k_1 e) \]
\[ + \frac{L}{p o \phi_f} (D_t^\alpha b o + D_t^\alpha \dot{t} + D_t^\alpha D_t^\alpha o_d + k_1 D_t^\alpha o_d) \]
\[ - \frac{j}{p o \phi_f} (b - k_1) [b o + t] \]
(25)

where \( k_1 \) and \( k_2 \) are feedback gains. Substitute (25) and (26) in (24) and (22),
\[ D_t^\alpha e_q = - \frac{k_2}{L_e} \frac{D_t^\alpha L_{eq}}{L} + \frac{\dot{L}}{L_e} \frac{D_t^\alpha i_q}{L} \]
\[ + \frac{D_t^\alpha j}{p o \phi_f} (b o + t + D_t^\alpha o_d - k_1 e) \]
\[ - \frac{j}{p o \phi_f} (D_t^\alpha b o + D_t^\alpha \dot{t} + D_t^\alpha D_t^\alpha o_d + k_1 D_t^\alpha o_d) \]
\[ - \frac{j}{p o \phi_f} (b - k_1) (e_o o + e_i) \]
(27)

To derive the stability conditions for the proposed controllers, the positive Lyapunov function for the entire control scheme can be defined as,
\[ V = \frac{1}{2} e^2 + \frac{1}{2} e_d^2 + \frac{1}{2} e_i^2 \]
\[ + \frac{1}{2} e_{eq}^2 + \frac{1}{2} e_{el}^2 + \frac{1}{2} e_{el}^2 + \frac{1}{2} e_{el}^2 \]
\[ + \frac{1}{2} e_{el}^2 + \frac{1}{2} e_{el}^2 + \frac{1}{2} e_{el}^2 \]
(31)

The Lyapunov first derivative of (31) is,
\[ \dot{V} = e_d \frac{D_t^\alpha e_d}{L} + 2 e_d \frac{D_t^\alpha e_d}{L} + 2 e_i \frac{D_t^\alpha e_i}{L} + \frac{e_d}{J} \frac{D_t^\alpha e_d}{L} \]
\[ + \frac{R_i}{L} \frac{D_t^\alpha e_i}{L} + \frac{e_d}{b} + \frac{e_d}{\tau} \]
(32)

Direct calculation of Lyapunov first derivative from Eq. (32) is difficult; hence, we derive a new lemma to find the sign of the Lyapunov derivative.

Hence we use the modified Lyapunov first derivative [27] and solve (31).

As defined by [27], if \( e(t) \) be a time continuous and derivable function, then for any time instant \( t \gg t_0 \),
\[ \frac{1}{2} D_t^\alpha e^2 (t) \leq x(t) \times D_t^\alpha x(t) \quad \forall q \in (0, 1) \]
(33)
Applying (33) in (31), a simple calculation shows that

\[
\dot{V} \leq p_{qf} e_{qf} e - k_{1e} e^2 - k_{3e}^2 - k_{2e_y}^2 \\
+ \frac{e_{qf} e_{qf}}{L} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{qf}^2 - k_{2e_y} e_{qf} \\
+ \frac{p_{qf} e_{qf}}{L} \left( e_{d} - k_{1} e_{d} - k_{2} e_{q} - k_{3} e_{q}^2 - k_{4} e_{q}^2 \right) \\
- \frac{p_{qf} e_{qf}}{L} \left( h e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - \frac{e_{d} e_{d}}{L} \left( e_{d} - k_{1} e_{d} - k_{2} e_{q} - k_{3} e_{q}^2 - k_{4} e_{q}^2 \right) \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d} \\
+ e_{d} D_{11} e_{d} \left( b e_\omega + \dot{\zeta} + D_{11} e_{qf} \right) - k_{1e} e_{d}^2 - k_{2e_y} e_{d}\]

(34)

To make the first derivative of the Lyapunov function a semi definite negative, we define the parameter update laws as,
\[ D_1^\dot{J} = \left( (b - k_1)l_2e_q - \dot{b} + \dot{\tau} + D_1^\dot{J} + k_1e \right) e \]
\[ D_1^\dot{R} = -(i_2e_2 + i_3e_3) \]
\[ D_1^\dot{b} = \frac{j}{p_D}(b - k_1)e_3 - coe \]
\[ D_1^\dot{z} = \frac{j}{p_D}(b - k_1)e_3 - e \]  

\[ D_1^\dot{L} = \left[ e_d(k_3e_d + p_oi_d) - e_q \right] \left[ -p_{oi_d} - k_2e_d + \frac{j}{p_D}(b + \dot{\tau} + D_1^\dot{J} + k_1e) \right] \]
\[ + \frac{j}{p_D}(D_1^\dot{b} + D_1^\dot{z}) \]
\[ + D_1^\dot{D}e_q + k_1D_1^\dot{J} \]
\[ + (b - k_1)l_4 - \frac{j}{p_D}(b - k_1)(b \dot{e} - \dot{\tau}) \]  

By updating the parameter estimates defined in (36) and (37) in (35),
\[ V \leq \frac{p_D}{p_D} \dot{e}_d - k_1e^2 - k_2e^2 - k_3e^2 \leq 0 \]
which is a negative semi definite if the constants \( k_1 \) and \( k_2 \) are defined to be,
\[ k_1 > \frac{p_D}{2J_{\text{min}}} \]
\[ k_2 > \frac{p_D}{2J_{\text{min}}} \]  

From (34) it is clearly seen that if the constants are selected as in (39), the proposed control scheme is asymptotically stable with an origin.

5. Numerical simulations and discussions

A control strategy based on fractional-order nonlinear controllers is considered for the variable speed operation of wind turbines with PMSG. In order to achieve the maximum torque per ampere, the \( d \)-axis current is set at zero. Thus, there will be a linear relationship between the electromagnetic torque and the \( q \)-axis current. We used LabVIEW with Control and Simulation loop for analyzing the numerical simulation results. The PMSG parameters for simulation are as follows: Type PMSG, 2.0 MW, 690 V, 9.75 Hz, non-salient pole, Rated Mechanical Power – 2.0 MW, Rated Apparent Power – 2.2419 MVA, Rated Power Factor – 0.8921, Rated Rotor Speed – 22.5 r/min, Number of Pole Pairs – 26, Rated Mechanical Torque – 848,826 Nm, Rated Rotor Flux Linkage – 5.8264 (rms), Stator Winding Resistance – 0.821, \( d \) axis Synchronous Inductance – 1.5731, \( q \) axis Synchronous Inductance – 1.5731.

The proposed nonlinear controllers from (25) and (26) with parameter update law (36) and (37) are implemented in LabVIEW and investigated for its performance.

Fig. 8 shows the design of the PMSG model in LabVIEW. The parameters for the design are taken as discussed above. Fig. 9 shows the proposed control scheme implemented with fractional order controllers. The PI blocks defined in the control scheme are the fractional nonlinear controllers proposed in (25), (26), and (36), (37). Figs. 10 and 11 show the current control and thus the speed control of the PMSG system for varying wind speeds. Figs. 12 and 13 show the current and speed control with an external uncertain disturbance.

Figure 11 Speed control and stabilizing with nonlinear controller.

Figure 12 Q axis current with nonlinear controller (Red – with disturbance, Blue – without disturbance).

Figure 13 Speed stabilizing with nonlinear controller (Red – with disturbance, Blue – without disturbance).
6. Conclusion

In this paper we have proposed a new nonlinear controller with fractional order to stabilize the speed of a PMSG and to control the $q$ axis current. The proposed controller was designed assuming that all the parameters of the PMSG are unknown and hence a parameter update law is introduced. As the Lyapunov exponents of the fractional order system and controller have to be derived to comment on the stability, we used a new methodology to find the sign of the Lyapunov first derivative. For the numerical simulations, the PMSG model and the proposed controllers are implemented in LabVIEW. The simulation results are investigated to prove the proposed control scheme.

References